A SIMPLIFIED DECODER FOR A BIT INTERLEAVED COFDM-MIMO SYSTEM

The present invention relates to a simplified decoder for a coded orthogonal frequency division multiplexing-multiple input multiple output (COFDM-MIMO) system. More particularly, the present invention relates to a bit interleaved system with maximum (ML) likelihood decoding. Most particularly the present invention relates to a 2 by 2 MIMO system with Zero Forcing (ZF) guided maximum likelihood (ML) decoding that doubles the transmission data rate of a single input single output (SISO) IEEE 802.11a system based on orthogonal frequency division multiplexing (OFDM) technique.

MIMO systems have been studied as a promising candidate for the next generation of high data rate wireless communication system. Currently, for a single antenna system (SISO), IEEE 802.11a employing the OFDM modulation technique has a maximum data transmission rate of 54 Mbps. There is only one transmission antenna and one receiving antenna, i.e., it is a SISO system, and the signal constellation for 802.11a is 64 quadrature amplitude modulation (QAM). Transmission data rates in excess of 100Mbps is a goal for the next generation wireless communication system.

Given the physical channel characteristics of wireless communication systems, it is almost impossible to increase the data rate with a single antenna system by increasing the order of the constellation of the signal.

One possible approach to achieving a greater than 100Mbps data rate is a 2 by 2 MIMO system based on an IEEE 802.11a SISO system in which the two transmission antennae transmit different data streams that are coded in the same way as an 802.11a system at each antenna. This system can achieve a transmission data rate of 108Mbps with approximately the same signal-to-noise ratio (SNR) as the prior art 54 Mbps IEEE 802.11a SISO system based on OFDM modulation that is illustrated in FIG. 1. FIG. 2 illustrates a prior art 2 by 2 MIMO system that could be used in this way.

Suppose the system of FIG. 2 employs optimal decoding and the wireless channel is defined as $H = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}$, where h_{ij} 20 represents the channel from transmitter antenna i to receiver antenna j, i.e., Txi to Rxj. Without losing generality, assume the four channels are Rayleigh fading channels that are independent of one another. Then the received signal in frequency domain on subcarrier k can be expressed as

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \qquad (1)$$

Since each subcarrier is decoded separately, the subscript ks in equation (1) is omitted. In optimal maximum likelihood (ML) detection, for each received signal pair, r_1 and r_2, to determine whether a transmitted bit in these symbols is '1' or '0', it is necessary to find the largest probability

$$\max(\ p(\boldsymbol{r} \mid b)) \qquad (2)$$

where $\boldsymbol{r} = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}$ and $\boldsymbol{b} = \begin{pmatrix} b_{1i} \\ b_{2i} \end{pmatrix}$ are the bits in symbol s_1 and s_2 for which a decision needs to be made. In an add white gaussian noise (AWGN) environment, this is equivalent to finding

$$\max_{s_m, s_n}\left(\frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|r_1 - h_{11}s_m - h_{21}s_n|^2}{2\sigma^2}} * \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{|r_2 - h_{21}s_m - h_{22}s_n|^2}{2\sigma^2}} \middle| b_{1i}, b_{2i}\right) \qquad (3)$$

$$= \max_{s_m, s_n}\left(\frac{1}{2\pi\sigma^2} e^{-\frac{|r_1 - h_{11}s_m - h_{21}s_n|^2}{2\sigma^2} - \frac{|r_2 - h_{21}s_m - h_{22}s_n|^2}{2\sigma^2}} \middle| b_{1i}, b_{2i}\right)$$

It is also equivalent to finding

$$\min_{s_m, s_n}\left(|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{21}s_m - h_{22}s_n|^2 \,\middle|\, b_{1i}, b_{2i}\right) \qquad (4)$$

In order to determine the bit metrics for a bit in symbol s_1, the following equation must be evaluated. For bit i in symbol s_1 to be '0', it is necessary to evaluate

$$m_{1i}^0 = \min_{s_m \in S^0, s_n \in S}\left(\left(|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2\right) \middle| b_{1i} = 0\right) \qquad (5)$$

Where m_{1i}^0 represents the bit metrics for bit i in received symbol s_1 to be '*0*'. S represents for the whole constellation point set, while S^0 represents the subset of the constellation point set such that bit $b_i = 0$. For bit i in symbol s_1 to be '*1*', it is necessary to evaluate

$$m_{1i}^1 = \min_{s_m \in S^1, s_n \in S}((|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2)|b_{1i} = 1) \quad (6)$$

where S^1 represents the subset of the constellation point set such that bit $b_i = 1$.

Using the same method, it is possible to determine the bit metrics for transmitted symbol s_2. For bit i in symbol s_2 to be '*0*', it is necessary to evaluate

$$m_{2i}^0 = \min_{s_m \in S, s_n \in S^0}((|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2)|b_{2i} = 0) \quad (7)$$

For bit i in symbol s_2 to be '*1*', it is necessary to evaluate

$$m_{2i}^1 = \min_{s_m \in S, s_n \in S^1}((|r_1 - h_{11}s_m - h_{21}s_n|^2 + |r_2 - h_{12}s_m - h_{22}s_n|^2)|b_{2i} = 1) \quad (8)$$

Then, the bit metrics pairs (m_{1i}^0, m_{1i}^1) (m_{2i}^0, m_{2i}^1) are sent to corresponding deinterleavers and Viterbi decoders for FEC decoding of each of the data streams.

Simulation results show that using optimal decoding, the proposed 108Mbps MIMO system actually performs 4dB better than the SISO 54Mbps system at a BER of 10^{-4}. However, the computation cost for the optimal decoding is very high. To obtain bit metrics for a bit in signal s_1 to be 0 and 1, it is necessary to evaluate 64*64 permutations of the s_1 and s_2 constellation, which cannot be accomplished cost effectively with existing computational capabilities. The computation cost for this 2 by 2 MIMO system decoding is too high to be practical.

Thus, there is a need for an alternative coding method to reduce the high computation cost when a 2 by 2 MIMO system based on and 54Mbps IEEE 802.11a SISO system is employed for increasing the data transmission rate above 100Mbps.

The present invention is a 108Mbps 2 by 2 MIMO system based on a 54Mbps SISO system, as illustrated in FIG. 3, that replaces optimal decoding with a simplified decoding method that has about the same computation cost as the optimal SISO decoder and about 1/64 the computation cost of the optimal MIMO decoder. In the system illustrated in FIG. 3, the separate demapping an deinterleaving module 10, of the prior art system illustrated in FIG. 1, is replaced by a shared demapping and signal separation unit 34 and the separate deinterleaving units 30 and 31.

The present invention employs a ZF guided maximum likelihood (ML) decoding method. For a SISO single carrier system, since a time-dispersed channel (frequency selective fading channel) brings the channel memory into the system, joint maximum likelihood (ML) equalization and decoding is not realistic because of the high computation cost. The general practice is to first use minimum-mean-square-error/ zero forcing (MMSE/ZF) as the criteria to equalize the channel. Then the equalized signal is sent to a maximum likelihood (ML) detector for further decoding. However, this is a sub-optimal system.

In a SISO OFDM system, since the system is designed to let each sub-carrier experience flat fading channel, the real maximum likelihood (ML) equalization and decoding can be implemented with affordable computational cost. Yet in a MIMO OFDM system, because of the large number of permutation evaluations of the constellation set required in the metrics calculation, the computation cost for real maximum likelihood (ML) equalization and decoding is too high to be practical.

One way to avoid the large number of permutation computations is to first find the approximate value of the transmitted symbols s_1 and s_2 and then use the maximum likelihood (ML) detection method to find the bit metrics for s_1 while taking s_2 as the value calculated by the ZF method. It is reasonable to make the assumption that when the SNR is high enough, the ZF decision is very close to the optimal maximum likelihood decision. Thus, the present invention incurs approximately the same computation cost in a MIMO system to get the bit metrics for the transmitted symbols s_1 and s_2 as the SISO system incurs for transmitted symbols s.

FIG. 1 illustrates a prior art 54 Mbps IEEE 802.11a SISO system based on OFDM modulation.

FIG. 2 illustrates a prior art 2 by 2 MIMO system.

FIG. 3 illustrates a 108Mbps 2 by 2 MIMO system based on the 54 Mbps SISO system of FIG. 1, according to a preferred embodiment of the present invention.

FIGs. 4A-C illustrate a Slice-Compare-Selection Operation.

FIG. 5 shows simulation results comparing the 108 Mbps MIMO system of FIG. 3 with the 54 Mbps SISO system of FIG. 1.

The preferred embodiments of the present invention employ a simplified decoding method. The details of the simplified decoding method are described below with reference to the drawings.

The received signal can be written as $\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}\begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$. According to the ZF criteria, the transmitted signal can be estimated by the demapping and signal separation module 34 as

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}^{-1} \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} \tag{9}$$

Using the minimum Euclidean distance calculated for the ZF calculated symbol and constellation point, the demapping and signal separation module 34 obtains the estimated transmitted symbol by hard decision. The symbols after the hard decision operation can be represented as $\begin{pmatrix} \hat{s}_1 \\ \hat{s}_2 \end{pmatrix}$. The bit metrics for transmitted symbol s_1 are then calculated by the demapping and signal separation module 34 as

$$m_{1i}^0 = \min_{s_m \in S^0}((|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2)|b_{1i} = 0)$$

$$m_{1i}^1 = \min_{s_m \in S^1}((|r_1 - h_{11}s_m - h_{21}\hat{s}_2|^2 + |r_2 - h_{12}s_m - h_{22}\hat{s}_2|^2)|b_{1i} = 1) \tag{10}$$

and bit metrics for transmitted symbol s_2 can then be calculated as

$$m_{2i}^0 = \min_{s_n \in S^0}((|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2)|b_{2i} = 0)$$

$$m_{2i}^1 = \min_{s_n \in S^1}((|r_1 - h_{11}\hat{s}_1 - h_{21}s_n|^2 + |r_2 - h_{12}\hat{s}_1 - h_{22}s_n|^2)|b_{2i} = 1) \tag{11}$$

where S^p represents the subset of the constellation points such that bit b_i is p where $p=0$ or 1. Then, the bit metrics pairs (m_{1i}^0, m_{1i}^1) (m_{2i}^0, m_{2i}^1) are sent to corresponding first and second deinterleavers 30 and 31 and different Viterbi decoders 33 and 34, respectively, for forward error correction (FEC) decoding of each data stream.

In a second preferred embodiment, a further simplified decoding method is provided based on the first preferred embodiment. Unlike the first preferred embodiment in which the demapping and signal separation module 34 uses the MIMO ML criteria to calculate the bit metrics for each bit in the two transmitted symbols after the ZF operation, the SISO ML is used by the demapping and signal separation module 34 to find the constellation points for each bit that satisfy

$$\min_{s \in S_i^p} \| \tilde{s}_q - s \|^2 \tag{12}$$

where $q = 1,2$ and $p \in \{0,1\}$. Two constellation points are defined by the demapping and signal separation module 34 that correspond to the bit metrics calculation of (12) for bit i of the transmitted symbol s_q to be s_{qi}^p. In SISO decoding, bit metrics calculated from (12) are sent to a Viterbi decoder for decoding. In MIMO decoding, equation (12) is only used by the demapping and signal separation module 34 to determine the constellation points that satisfy (12) and use these constellation points in MIMO ML criteria to calculate the bit metrics for each bit that are sent to a Viterbi decoder for decoding. That is, the bit metrics are calculated by the demapping and signal separation module 34 as

$$\begin{aligned} m_{1i}^p &= (\| r_1 - h_{11} s_{1i}^p - h_{21} \hat{s}_2 \|^2 + \| r_2 - h_{12} s_{1i}^p - h_{22} \hat{s}_2 \|^2) \\ m_{2i}^p &= (\| r_1 - h_{11} \hat{s}_1 - h_{21} s_{2i}^p \|^2 + \| r_2 - h_{12} \hat{s}_1 - h_{22} s_{2i}^p \|^2) \end{aligned} \tag{13}$$

Then, the bit metrics pairs (m_{1i}^0, m_{1i}^1) (m_{2i}^0, m_{2i}^1) are sent to corresponding first and second deinterleavers 30 and 31 and different Viterbi decoders 33 and 34, respectively, for forward error correction (FEC) decoding of each data stream.

In a hardware implementation, the 12 constellation points for the 6 bits in one transmitted symbol can be obtained by a slice-compare-select operation. An example of quadrature-phase shift keying (QPSK) is illustrated in Fig.4A. If the real part of the received symbol is considered, it is possible to determine that the two constellation points corresponding to bit b_0 are the two points connected by the dashed line in FIG. 4B. The same method can be used to determine the corresponding constellation points for bit b_1 by using the imaginary part of the received symbol, as shown in FIG. 4C. With the slicing method, the actual distance calculation of equation (12) is not needed. In the second preferred embodiment, the permutation in distance searching in the MIMO ML bit metrics

calculation can be avoided, which reduces the computation cost of the MIMO ML bit metrics calculation.

Simulation results, shown in FIG. 5, confirm the performance of both embodiments of the present invention. The multipath channel simulated is the exponential Rayleigh fading channel defined in Bob O'Hara, Al Petrick; "The IEEE 802.11 Handbook: A Designer's Companion", December 1999, having a 40ns rms delay spread. The four channels across the two transmission antennae and two receiving antennae are independent of each other, which means there is no correlation between any of the four channels. For each data point of the sign-to-noise-ratio vs. bit-error-rate (SNR vs. BER) curves of FIG. 5, 1 million bits equally distributed in 250 packets was simulated. It is reasonable to assume that the wireless channel for each antenna element is the same for each packet, while it is different for different packets. In all the simulations, ideal frequency and timing synchronization is assumed.

Simulation results show that although the performance of the first embodiment of the simplified decoding method of the present invention is about 4dB worse than the optimal decoding method at a BER level of 10^{-4}, it is almost the same as the optimal decoding for the SISO system at 54Mbps 43. This result shows that the first embodiment of the present invention comprising a 2 by 2 MIMO system 41 can double the transmission data rate of the SISO system 43 for the same SNR at reasonable computation cost. The second embodiment provides the same improvement for a further reduced computation cost. Therefore, the simulation show that both embodiments of the present invention have about the same BER vs SNR performance, which is almost the same as SISO 54Mbps system 43 and 4dB less than MIMO optimal decoding system 42 at BER level of $10^{-4.}$ And, the increase in transmission rate by double is obtained for no increase in computation cost in the first embodiment and a reduced computation cost in the second embodiment

Referring to FIG. 4, a 2 by 2 MIMO system 42 based on IEEE 802.11a SISO system according to the present invention can provide a 108Mbps transmission data rate that doubles the data rate of the IEEE 802.11a SISO system within the same range of SNR. Optimal decoding of the MIMO system 42 according to the prior art provides 4dB better BER vs. SNR performance than the SISO 54Mbps system 43 at BER level of 10^{-4} but the high computation cost of the optimal decoding makes such an implementation impractical. The present invention provides two preferred embodiments for ZF guided simplified

MIMO decoding, 40 and 41, having computation costs that are almost the same as that of the optimal decoder for the 54Mbps SISO system 43. Although each of the embodiments for a simplified method, 40 and 41, performs 4dB worse than the optimal decoder for MIMO system 42, each provides almost the same SNR performance as the SISO 54Mbps system 43 at the BER level of 10^{-4}, but at the transmission data rate of 108Mbps

While the examples provided illustrate and describe a preferred embodiment of the present invention, it will be understood by those skilled in the art that various changes and modifications may be made, and equivalents may be substituted for elements thereof without departing from the true scope of the present invention. In addition, many modifications may be made to adapt the teaching of the present invention to a particular situation without departing from the central scope. Therefore, it is intended that the present invention not be limited to the particular embodiments disclosed as the best mode contemplated for carrying out the present invention, but that the present invention include all embodiments falling within the scope of the appended claims.